Threshold-based Filtering Buffer Management Scheme in a Shared Buffer Packet Switch

Jui-Pin Yang, Ming-Cheng Liang, and Yuan-Sun Chu

Abstract: **In this paper, an efficient threshold-based filtering (TF) buffer management scheme is proposed. The TF is capable of minimizing the overall loss performance and improving the fairness of buffer usage in a shared buffer packet switch. The TF consists of two mechanisms. One mechanism is to classify the output ports as active or inactive by comparing their queue lengths with a dedicated buffer allocation factor. The other mechanism is to filter the arrival packets of inactive output ports when the total queue length exceeds a threshold value. A theoretical queuing model of TF is formulated and resolved for the overall packet loss probability. Computer simulations are used to compare the overall loss performance of TF, dynamic threshold (DT), static threshold (ST) and pushout (PO). We find that TF scheme is more robust against dynamic traffic variations than DT and ST. Also, although the overall loss performance between TF and PO are close to each other, the implementation of TF is much simpler than the PO.**

Index Terms: **Threshold, filtering, buffer management, fairness, robust.**

I. INTRODUCTION

When arrival packets are simultaneously routed to the same destination, most packet switches utilize buffering methods to deal with resource contention. The performance metrics (delay, packet loss probability, and fairness *et al.*) of a packet switch [1] as such can be significantly affected by buffer location and management schemes. It was concluded that mechanisms of output-queued buffer and completely shared buffer are able to achieve optimal throughput-delay performance.

In general, an output-queued shared buffer packet switch may perform badly under congested traffic conditions if the buffer usage [2] has no adequate buffer management policies in place. For example, a high traffic output port may overtake majority of the buffer space and prevent arrival packets of other output ports from entering the buffer. The result will be a great increase in overall packet loss probability and an imbalanced buffer usage between different output queues. One way to resolve the problem is to limit the buffer size that can be used by an output port. Applying such limits will ultimately result in creating reserved buffer sizes for other output ports. Obviously, if too much buffer space is reserved, this will cause a low buffer utilization. Therefore, designing a good buffer management scheme is critical for achieving a high performance packet switch.

In this paper, we mainly focus on studying the performance of overall packet loss probability and fairness. To minimize the overall packet loss probability is the same as to maximize the overall switch throughput and buffer utilization. To provide fairness of buffer usage among different output ports, the queue lengths of output ports are smaller than the buffer size which must be able to increase in length. This will only affect the arrival packets destined to congested output ports, and those destined to light traffic output ports will not be affected.

Some well-known buffer management schemes, such as complete partitioning (CP), complete sharing (CS), sharing with maximum queue lengths (SMXQ), sharing with a minimum allocation (SMA), and sharing with a maximum queue and minimum allocation (SMXQA) [2], [3], limit the maximum or minimum amount of buffer space available to individual output queue. In this paper, we consider one version of this approach called static threshold (ST) scheme. In the ST, an arrival packet is allowed to enter the buffer only if the queue length of its destination output port is smaller than a given threshold value. Although the ST is easily implemented and extended to multiple loss priorities, it only performs well under certain traffic conditions.

Recently, some dynamic threshold buffer management schemes were proposed [4]–[10]. Due to space limitations, we will only consider the dynamic threshold (DT) scheme [4], [5]. The main idea behind the DT is that the threshold for individual output queue is controlled by a DT factor, which is proportional to the unused buffer size in the packet switch. When the queue length of an output port exceeds the threshold value, then no arrival packet is accepted for that output port. However, an improper value of DT factor may cause the DT scheme to fail.

To improve the drawbacks of ST and DT, the pushout (PO) scheme is proposed [11]–[17]. In the PO, all arrival packets are admitted to the buffer before the buffer is full. When the buffer is full, the arrival packet will push out the packet at the head of the longest output queue. The PO possesses some performance merits. PO is fair in the sense that it allows smaller queues to increase in length by pushing out packets in the longest output queue. PO is efficient because it maintains high buffer utilization through leaving no buffer space on idle. PO is also adaptive since the contention keeps the queue lengths short when there are more than one greedy output queues and increases the queue length when there is only one greedy output queue.

Although the performance of PO is very good, it has some drawbacks, especially in the implementation. First, it needs to

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determine the longest output queue and track the address of the pushed out packet with sufficient buffer space in order to accommodate the arrival packet with variable lengths. Also, it is difficult to extend the PO for multiple loss priorities [18]. These difficulties make it hard to adopt the PO scheme as a suitable buffer management scheme for high-speed packet switch.

Instinctively, a buffer management scheme with the simplicity of ST and the dynamic adjustability of PO is desired, so we proposed the threshold-based filtering (TF) scheme to meet these requirements. The key idea of the TF is to separate the output ports into active and inactive output ports according to whether their queue lengths are larger than the dedicated buffer allocation factor or not. Next, when the total queue length is smaller than the TF threshold factor subtracted by the total buffer, all arrival packets are accepted. Otherwise, only arrival packets destined to inactive output queues are admitted to the buffer.

The rest of this paper is organized as follows. Section II describes the detailed operation of TF scheme. In Section III, we establish the queuing model of TF and then resolve the overall packet loss probability. In Section IV, we show the simulation results. The switch architecture and "ON-OFF" input traffic model are introduced in Section IV-A. In Section IV-B, a comparison of the overall loss performance for TF, DT, ST, and PO are presented. To provide more solid TF analysis, we also added the performance study of TF under Poisson arrival in the last part of Section IV-B. The conclusions and future works are presented in Section V.

II. THRESHOLD-BASED FILTERING SCHEME

The TF scheme is designed to use the shared buffer efficiently and fairly. It means to minimize the overall packet loss probability and guarantee the fair buffer usage among different output ports. The output ports are classified into active or inactive output ports based on their queue lengths. The classification is based on the dedicated buffer allocation factor (B/N) where B is the total buffer size and N is the number of output ports as in definition 1. By reserving sufficient buffer size for all inactive output ports under overloaded mode as in definition 2, the TF can protect the arrival packets that are destined to inactive output ports from being dropped out.

Definition 1: If the queue length of output port i is larger than B/N, then the output port i is called an *active output port*; otherwise, it is called an *inactive output port.*

Definition 2: If the total queue length is larger than $B - T$, then the state of packet switch is called *overloaded mode*; otherwise, it is called *non-overloaded mode* where T is the TF threshold factor in this scheme.

The value of T should be kept as small as possible, so that much more buffer space can be shared and used by all output ports. This can increase the buffer utilization. However, a very small value of T will cause most of arrival packets that are destined to inactive output ports to be discarded, because the reserved buffer space is insufficient. In this situation, the buffer behavior of TF is similar to the drop-tail of the CS, so the overall packet loss probability will be largely increased. Next, we show the operation of TF scheme under non-overloaded mode.

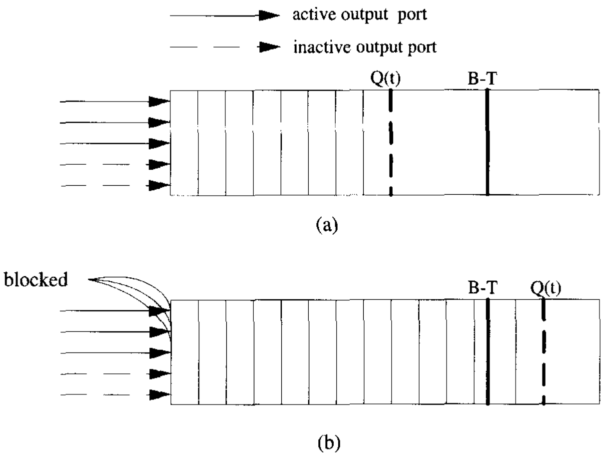

Fig. 1. Operation of threshold-based filtering scheme: (a) Non-overloaded mode ($Q(t) \leq B - T$), (b) overloaded mode ($Q(t) > B - T$).

$$X_i(t) = A_i(t), \quad i = 1, 2, 3, \cdots, N, \tag{1}$$

where $X_i(t)$ is the maximum allowable buffer size for output ports i at time t and $A_i(t)$ is the number of all incoming packets destined to output port i at time t.

When the switch state is in non-overloaded mode, the operation of TF is depicted in Fig. 1(a). In Fig. 1(a), all arrival packets are admitted to the buffer regardless of whether their destinations are active or inactive output ports where $Q(t)$ is denoted as the total queue length at time t. Therefore, the maximum allowable buffer size for output port i at time t is equal to the number of all incoming packets destined for output port i at time t. Subsequently, (2) is used to show the operation of TF scheme under overloaded mode.

$$X_i(t) = \begin{cases} A_i(t) & i \in S_{in}(t) \\ 0 & i \in S_a(t), \end{cases} \tag{2}$$

where $S_a(t)$ is the set of active output ports at time t and $S_{in}(t)$ is the set of inactive output ports at time t.

When the switch state is in overloaded mode, the operation of TF is depicted in Fig. 1(b). In Fig. 1(b), the TF starts to filter the arrival packets according to their destinations. If the arrival packets are destined to the active output ports, the filter simply blocks all of the arrival packets. On the other hand, if the arrival packets are destined to the inactive output ports, all of them are admitted to the buffer. With an adequate value of T, the TF can guarantee the arrival packets that are destined to inactive output ports to enter the buffer. It means that the TF does not limit the inactive output ports to increase in length, unless they are transferred to active output ports. Therefore, the TF is able to provide fairness and an overall low packet loss probability.

III. QUEUING MODEL

The queuing model of a shared buffer packet switch is depicted in Fig. 2. There are N logical output queues that share a buffer capacity of size B. An arrival packet destined to output port i is called a type i packet. When total queue length is

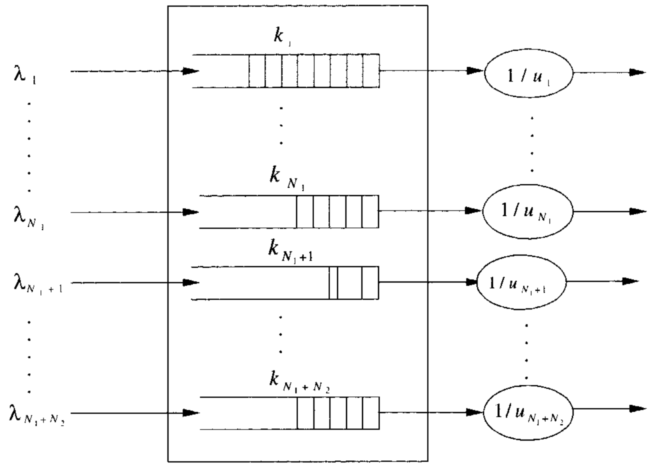

Fig. 2. Queuing model of a shared buffer packet switch.

smaller than $B-T$, all arrival packets are admitted to enter and share the buffer capacity; otherwise, only arrival packets destined to inactive output ports are capable of sharing the residual buffer size T. The input traffic for each output queue i is characterized by a Poisson arrival with the mean rate λ_i and the service time is an exponential random variable with mean $1/u_i$. Queued packets of type i are served on a first-in first-out basis. For simplicity, we also assume the queuing system under TF scheme with N_1 inactive output queues ($1, 2, 3, \cdots, N_1$) and N_2 active output queues ($N_1+1, \cdots, N$) where $N_1+N_2=N$. The queuing analysis is separated into two cases according to whether Q is larger than $B-T$ or not, where Q is the steady state of the total queue length.

Case (1): $Q \leq B-T$

The entire system can be viewed as a birth-death process [19], whose state can be described by the vector $\vec{k} = (k_1, k_2, k_3, \cdots, k_N)$ where k_i is the nonnegative random variable that denotes the number of type i packets residing in the corresponding output queue i. The steady state probability distribution of the system state has the product form solution and is described as follows, i.e.,

$$P(k_1,k_2,k_3,\cdots,k_N) = \begin{cases} P(\vec{k}) = P_0(\rho_1^{k_1}\rho_2^{k_2}\rho_3^{k_3}\cdots\rho_N^{k_N}), & for\ \vec{k} \in F_a \\ 0, & otherwise, \end{cases} \tag{3}$$

$$F_a = \left\{ \vec{k} \mid \sum_{i=1}^{N} k_i \leq B-T \right\}. \tag{4}$$

We define the utilization of output queue i to be $\rho_i = \lambda_i/u_i$. The F_a represents the set of possible system states in this case and P_0 is the probability of no packets residing in this system. First, let us define $G(K)$ as

$$G(K) = \sum_{0\leq k_i\leq K,\ \sum_{i=1}^{N} k_i = K} \rho_1^{k_1}\rho_2^{k_2}\rho_3^{k_3}\cdots\rho_N^{k_N}, \quad K = 0,1,2,3,\cdots,B-T. \tag{5}$$

Here, we use the complex analysis approach [20] to derive the closed form expression of $G(K)$ which exhibits the interrelationships among the system variables. We get the $G(K)$ is as follows

$$G(K) = \sum_{i=1}^{N} A_i\rho_i^K, K = 0,1,2,3,\cdots\cdots, B-T, \tag{6}$$

where $A_i = \sum_{k=1,k\neq i}^{N} \frac{1}{(1-\rho_k/\rho_i)}$.

Case (2): $Q > B-T$

In this case, all arrival packets that are destined to active output queues are dropped, and only arrival packets that are destined to inactive output queues are admitted to the buffer. It means that residual buffers of size T are just shared by N_1 inactive output queues, so the queuing behavior of system states is similar to (3) and (4). We get

$$P(b_1,b_2,b_3,\cdots,b_{N_1}) = \begin{cases} P(\vec{b}) = P_0(\rho_1^{b_1}\rho_2^{b_2}\rho_3^{b_3}\cdots\rho_{N_1}^{b_{N_1}}), & for\ \vec{k} \in F_b \\ 0, & otherwise, \end{cases} \tag{7}$$

$$F_b = \left\{ \vec{b} \mid \sum_{i=1}^{N_1} b_i \leq T \mid \sum_{i=1}^{N} k_i \leq B-T \right\}. \tag{8}$$

The system state variables can be described by the vector $\vec{b} = (b_1, b_2, b_3, \cdots, b_{N_1})$ where b_i is denoted as the number of type i packets residing in the inactive output queue i. The F_b represents the set of possible system states. From (6), (7) and (8), we can get

$$G(J+B-T) = \sum_{i=1}^{N_1} B_i\rho_i^J G(B-T), J = 1,2,3,\cdots,T, \tag{9}$$

where $B_i = \sum_{k=1,k\neq i}^{N_1} \frac{1}{(1-\rho_k/\rho_i)}$. The Conversation Relation Law is

$$\sum_{\vec{k}\in F_a,F_b} P(\vec{k}) = 1. \tag{10}$$

From (10) and solving yields

$$P_0^{-1} = \sum_{K=0}^{B} G(K). \tag{11}$$

We show the packet loss probability of inactive output queue i is

$$L_i = P_0 G(B), \qquad i = 1,2,3,\cdots,N_1. \tag{12}$$

As for the packet loss probability of active output queue j is

$$L_j = P_0 \sum_{k=B-T+1}^{B} G(B), \quad j = N_1+1,\cdots,N. \tag{13}$$

The overall packet loss probability for any packet arriving at the packet switch is a weighted sum of the above; By (12) and (13), the overall packet loss probability L is

$$L = \sum_{i=1}^{N} p_i L_i, \tag{14}$$

where $p_i = \lambda_i / \lambda$ and $\lambda = \sum_{k=1}^{N} \lambda_k$.

IV. NUMERICAL RESULTS

In this section, we show the simulation results that compare the overall packet loss probabilities for the TF, DT, ST, and PO strategies. In Section IV-A, the switch and traffic model in this simulation are presented. In Section IV-B, the robustness of the three threshold buffer management schemes for achieving optimal overall loss performance are discussed.

A. Switch and Traffic Model

We assume the switch with N input ports and N output ports are running at the same rates. Packets arrive from one of the input ports, go through the switch fabric, join their destination output queues in the shared buffer, and then departure from their output queues on a first-in first-out (FIFO) basis. The switch fabric consists of NxN self-routing switch elements that route each incoming packet to its appropriate output port by inspecting the packet header. Assuming that the transition probability of the packet from input port i to output port j is denoted by $P_{i,j}$, we have

$$\sum_{j=1}^{N} P_{i,j} = 1, \quad i = 1, 2, 3, \cdots, N. \tag{15}$$

In order to emulate real traffic, an "ON-OFF" source model is used to represent the traffic model for each input port. The source model consists of two states, the "ON" state and the "OFF" state. The durations of the "ON" and "OFF" states follow geometric distributions with parameter $P_{on\text{-}off}$ and $P_{off\text{-}on}$, respectively. $P_{on\text{-}off}$ represents the transition probability from "ON" state to "OFF" state and $P_{off\text{-}on}$ represents the transition probability from "OFF" state to "ON" state. While the system is in "ON" state, one or zero packet is generated. Given the $P_{on\text{-}off}$ and $P_{off\text{-}on}$, we can determine the mean burst length of "ON" state $L_{on\text{-}off}$, the mean burst length of "OFF" state $L_{off\text{-}on}$, and the input traffic load ρ as follows:

$$L_{on\text{-}off} = \sum_{k=1}^{\infty} k P_{on\text{-}off} (1 - P_{on\text{-}off})^{k-1} = 1/P_{on\text{-}off},$$

$$L_{off\text{-}on} = \sum_{k=1}^{\infty} k P_{off\text{-}on} (1 - P_{on\text{-}off})^{k-1} = 1/P_{off\text{-}on},$$

$$\rho = \frac{L_{on\text{-}off}}{L_{on\text{-}off} + L_{off\text{-}on}}. \tag{16}$$

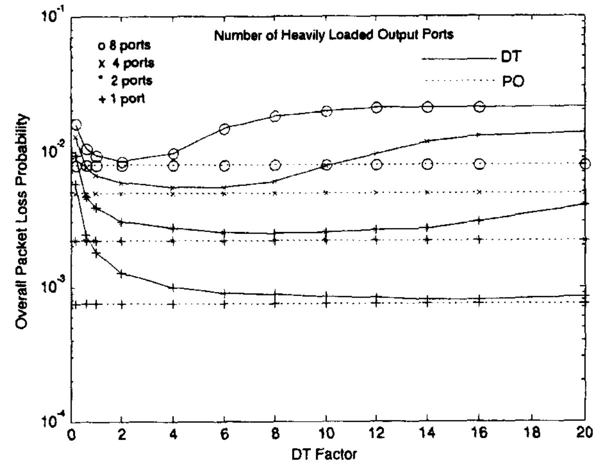

Fig. 3. Overall packet loss probability versus DT factor for various number of heavily loaded output ports.

B. Robustness of the Three Threshold Schemes

In this subsection, simulation results for various values of threshold factors in TF, DT and ST are compared under different traffic conditions. Moreover, to observe the robustness for achieving optimal overall loss performance, one will compare the situation when the threshold factor can't be returned. Unless stated otherwise, the following parameters are assumed throughout the simulation. The packet switch has 16 input ports, 16 output ports, and total buffer size is set at 256 packets. Also, the mean burst length of "ON-OFF" source model applied to each input port is set at 10. For simplicity, we also assume the packet length is a fixed size, and only one packet can be transmitted in a single time slot. The output ports are classified into heavily and lightly loaded output ports according to the mean offered loads. In the first case, the mean load of all lightly loaded output ports is set at 0.2489 and the mean load of all heavily loaded output ports is set at 0.9957.

In Figs. 5, 3, and 4, the TF, DT, and ST versus PO are compared under different numbers of heavily loaded output ports. The overall packet loss probabilities of ST, DT and TF vary with the threshold factors. However, whichever threshold factor is selected, the PO always performs better than ST, DT and TF. There are two reasons. First, PO can immediately retrieve buffer space from a long output queue, where as ST, DT, or TF can only reduce a queue's length by blocking new arrival packets. Second, PO allows all of the buffer space to be used at all times, while ST, DT, or TF holds only some of the buffer space in reserve. The PO is the horizontal flat line and is used as optimal overall loss performance.

In Fig. 5, the adequate setting value of TF factor ranges from 16 to 24. Any setting value of TF factor in this range will yield near optimal overall loss performance. When the setting value of TF factor increases to over 24, the overall packet loss probability is increased slowly. Because much more buffer space is reserved for inactive output ports to guarantee their throughput and fairness, the amount of unused buffer space will cause low buffer utilization.

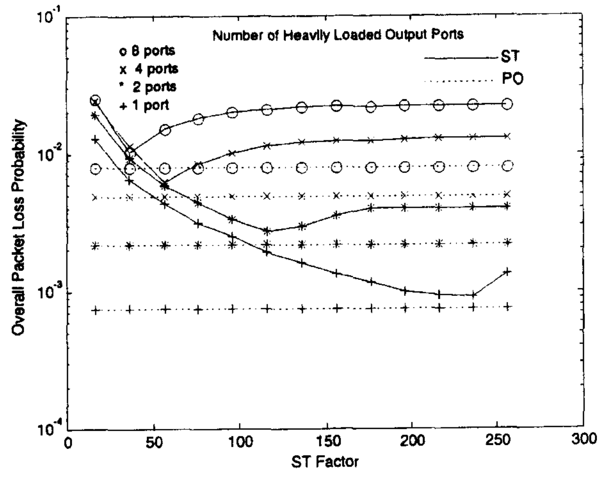

Fig. 4. Overall packet loss probability versus ST factor for various number of heavily loaded output ports.

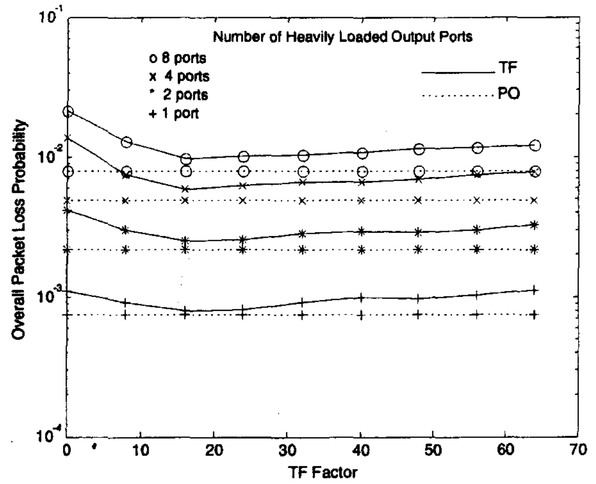

Fig. 5. Overall packet loss probability versus TF factor for various number of heavily loaded output ports.

When the setting value of TF factor decreases below 16, the overall packet loss probability is increased quickly. Because a small buffer size is reserved, most arrival packets that are destined to lightly loaded output ports are discarded due to the full buffer. In this case, TF scheme can't improve the fairness and overall packet loss probability. Specially, when the setting value of TF factor is at 0, the buffer behavior of TF is equivalent to the CS (Drop-Tail). The result is that many arrival packets that are destined to lightly loaded output ports are discarded even if their output links are idle. As a result, the overall packet loss probability is increased greatly.

In Fig. 3, the adequate setting value of DT factor is different and it ranges from 0.6 to 20. There is no stable setting value of DT factor to achieve near optimal overall loss performance and fairness simultaneously. For example, when the setting value of DT factor is at 1.0, and then one, two, and four heavily loaded output port cases have high overall packet loss probabilities. This is because most of the buffer space is reserved and unused. However, the DT can provide fair buffer usage for lightly loaded output ports in this case. When the setting value of DT factor is at 10, the overall packet loss probabilities in one and two heavily loaded output port cases are near optimal overall packet loss probability, but the four and eight heavily loaded output port cases have high overall packet loss probabilities. Also, the DT can't provide fairness for the conditions in two, four, and eight heavily loaded output port cases. The reason is that DT allocates too much buffer space for heavily loaded output ports and many arrival packets that are destined to lightly loaded output ports are discarded.

In Fig. 4, the adequate setting value of ST factor is greatly different and it ranges from 32 to 240. For example, when the setting value of ST factor is at 32, then two, four and eight heavily loaded output port cases have very high overall packet loss probabilities, because too much buffer space is reserved for lightly loaded output ports. But, the ST can provide fairness in this case. When the setting value of ST factor is at 240, the overall packet loss probabilities in eight heavily loaded output port case reaches near optimal overall loss performance. However, the one, two and four heavily loaded output port cases have high overall packet loss probabilities. Besides, the ST also can't support fairness for the conditions in one, two, and four heavily loaded output port cases. The reason is that most of the buffer size is occupied by the heavily loaded output ports. In the sense, TF is more robust than ST and DT to changes in the number of heavily loaded output ports.

In the second case, the mean load of all lightly loaded output ports is set at 0.6223 and the mean load of all heavily loaded output ports is set at 0.9957. In Fig. 6, the adequate setting value of TF factor also ranges from 16 to 24. Specially, the overall packet loss probabilities for the TF in all simulated cases are similar if the setting value of TF factor is from 0 to 8. Because the mean load of all lightly loaded output ports is increased from 0.2489 to 0.6223, the reserved buffer space for arrival packets that are destined to lightly loaded output ports must be increased. Therefore, the TF shows the drop-tail behavior as the CS. In Fig. 7, the adequate setting value of DT factor is still different and it ranges from 0.6 to 10. In Fig. 8, the adequate setting value of ST factor differs widely and it ranges from 32 to 200. Via above simulation results, we find that no stable setting value of ST and DT factors can get near optimal loss performance. In the sense, TF is more robust than ST and DT to changes in different numbers of heavily loaded output ports with various loads.

In the third case, we consider the effect of various total buffer sizes with eight heavily loaded output ports. Besides, the other traffic conditions are the same as Figs. 6, 7, and 8. In Figs. 9, 10, and 11, the adequate setting value of TF factor keeps the same value as all cases above. As for the DT, the adequate setting value of DT factor differs from 4 to 20. Lastly, the adequate setting value of ST factor ranges from 64 to 768. In the sense, TF is more robust than ST and DT to changes in various total buffer sizes.

In the fourth case, we discuss the performance effect on the TF scheme when Poisson arrival is assumed as the input traffic. In Fig. 12, when the mean loading changes, the adequate setting value of TF factor continues to range from 16 to 24. It means

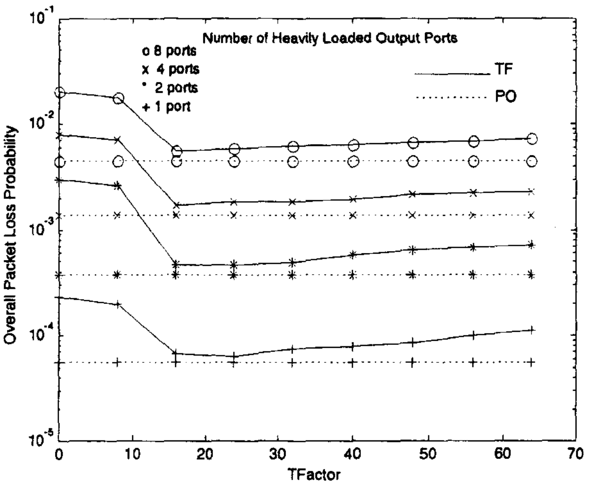

Fig. 6. Overall packet loss probability versus TF factor for various number of heavily loaded output ports.

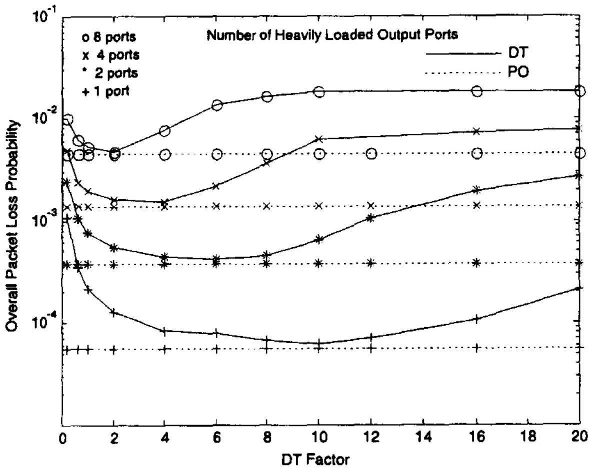

Fig. 7. Overall packet loss probability versus DT factor for various number of heavily loaded output ports.

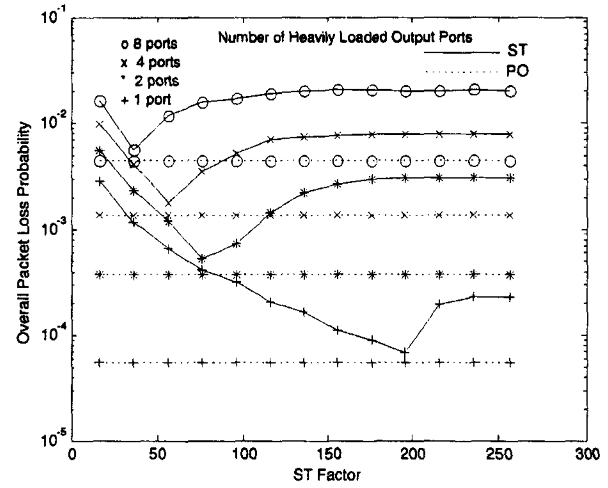

Fig. 8. Overall packet loss probability versus ST factor for various number of heavily loaded output ports.

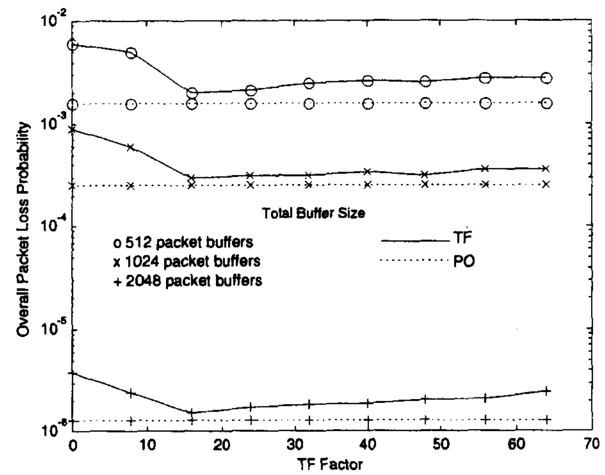

Fig. 9. Overall packet loss probability versus TF factor for various total buffer sizes with eight heavily loaded output ports.

the TF scheme is very robust again. However, the overall packet loss probability decreases as the mean offered loading for each individual lightly loaded output port is increased from 0.2499 to 0.4998. This can be explained by the definition of packet loss probability $(\lambda_{in} - \lambda_{out})/\lambda_{in}$. Where λ_{in} denotes the mean rate of incoming packets and λ_{out} denotes the departure rate from the shared buffer. When the mean loading of lightly loaded output ports increases, it means that the output ports will become more busy. Therefore, the overall packet loss probability has decreased. Of course, the behavior will be inversed if the mean loading of lightly loaded output ports exceeds some threshold value. In the sense, the TF is robust to changes in different input traffic models.

V. CONCLUSION

In a shared buffer packet switch, buffer management schemes can improve the fairness of buffer usage among different output ports and the overall loss performance. The ST and DT schemes may work well as long as their threshold factors are tuned properly according to traffic conditions. Otherwise, the ST and DT may perform badly under many kinds of traffic variations. In order to deal with this problem, the TF scheme is proposed in this paper. The TF not only possesses the adaptability of PO but also the simplicity of ST, so the TF is suitable for high-performance and high-speed packet switches. In our simulation results, when the setting value of TF factor ranges from 16 to 24, the TF can provide the fairness and near optimal overall loss performance under different traffic conditions.

In further works, we would like to extend the TF to support different loss priority classes while keeping the simplicity and adaptability. Also, we want to survey the effects of various packet lengths. Besides, in the recent studies [21]–[23], it was found that traffic model based on real traffic could better characterize the Internet traffic. Although the TF scheme is shown only

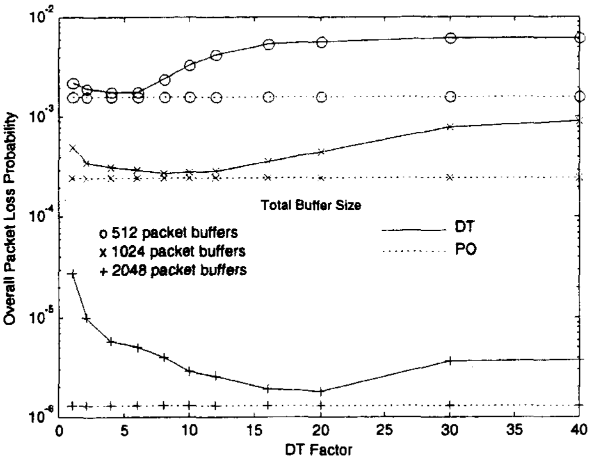

Fig. 10. Overall packet loss probability versus DT factor for various total buffer sizes with eight heavily loaded output ports.

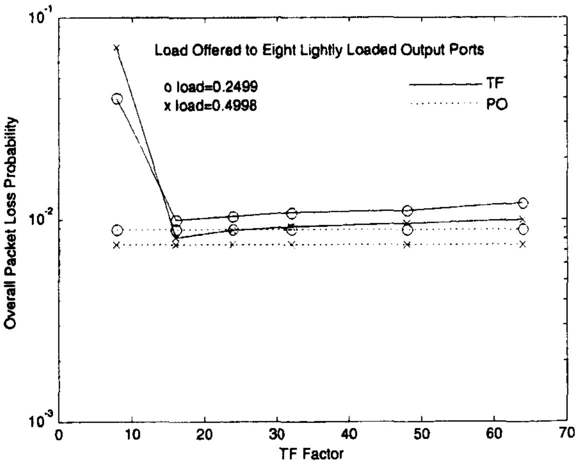

Fig. 12. Overall packet loss probability versus TF factor for various loads offered to eight lightly loaded output ports under Poisson arrival.

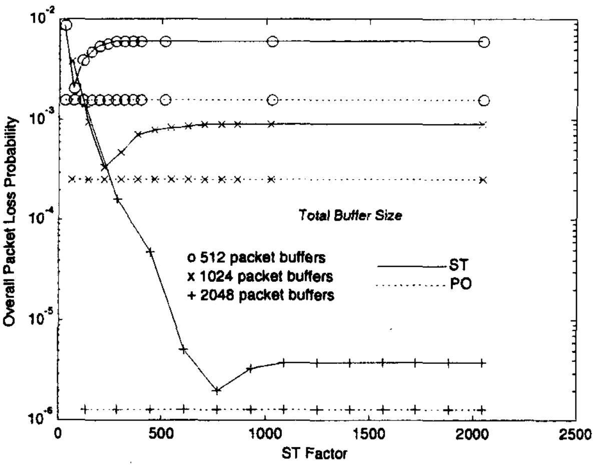

Fig. 11. Overall packet loss probability versus ST factor for various total buffer sizes with eight heavily loaded output ports.

for Poisson process, i.e., random traffic, it is expected that TF scheme could work well under these real traffic patterns (smooth or rough). A solid study to show how TF scheme compare with other schemes such as DP [6] and VP [7] under these traffic models will be the topics for our next study.

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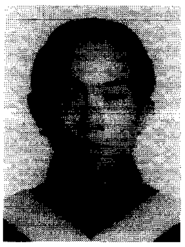

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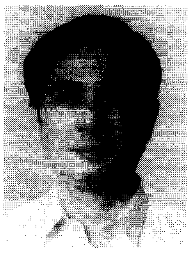

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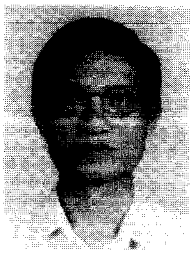

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